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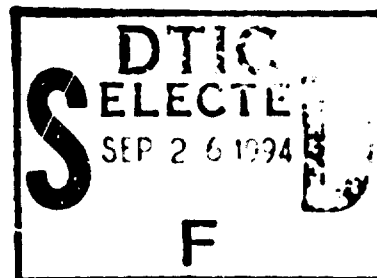
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A Study of High-Temperature Oscillating Plain Bearings

W. A. GLAESER

Assistant Division Chief,
Bearings Seals and Lubrication
Section, Battelle Memorial
Institute, Columbus, Ohio.



A heavy pendulum device was used to evaluate lubricants and bearing materials in the development of high-temperature airframe bearings. The method used in utilizing this principle for measuring friction coefficients at high temperatures is described. A few materials were found to be outstanding in performance at temperatures as high as 1500 F. Analysis of the wear surfaces indicated that good performance was associated with the formation of a thin complex oxide layer. The pendulum was found to be an effective means for quickly and inexpensively screening materials and lubricants for high-temperature, heavily loaded oscillating plain bearings.

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A Study of High-Temperature Oscillating Plain Bearings

W. A. GLAESER

During an investigation of materials and lubricants for high-temperature (to 1500 F) plain airframe bearings (1),¹ a number of materials were evaluated under simulated operating conditions. To achieve the necessary high temperature and oscillating motion for materials studies, an apparatus based on the principle of damped pendulum motion was developed and found effective as a screening device. Out of a number of materials and lubricants evaluated in this apparatus, a few were found outstanding in performance. Subsequent post-test analyses of these promising materials revealed surface conditions which are considered significant for good high-temperature-bearing performance.

The purpose of this paper, therefore, is to describe the principles of the pendulum-screening device and to discuss the reasons for apparent good performance of some materials as high-temperature oscillating bearings.

THE HIGH-TEMPERATURE PENDULUM

The evaluation of bearings at elevated temperatures involves considerable difficulty and usually expensive, complicated apparatus. Applying a load and driving bearings heated to a dull red heat often raises frustrating problems in maintaining alignment, in creep of supports, and thermal insulation of drive mechanisms. In attempting to find a way to evaluate the performance of selected materials and lubricants quickly and inexpensively, a method was devised which circumvents many of these problems. This method involved the use of a free-swinging pendulum in which the friction could be determined from the damping of the pendulum bearing. This principle has been used by others for the study of lubrication phenomena. Kyropoulos (2) in 1937 found that he could detect viscous effects in boundary-

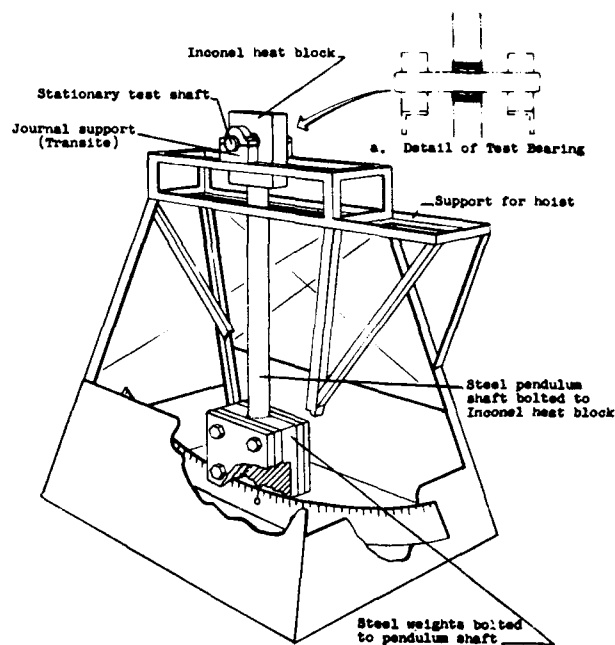


Fig.1 Pendulum bearing-material screening apparatus

lubrication experiments using a lightly loaded pendulum apparatus. Talley (3) of Shell Development Corporation has operated a pendulum device for the investigation of film-strength properties of greases at various temperatures with very good reproducibility.

The Battelle pendulum apparatus consisted of a heavily weighted arm attached to a housing containing a sleeve bearing and this assembly supported by a stationary shaft specimen. A schematic diagram of the apparatus is shown in Fig.1. In order to attain bearing stresses in the order of 10,000 psi, the contact area of the pendulum sleeve bearing was reduced by machining a wide circumferential groove in the center of the bearing, thereby providing two relatively narrow lands for the bearing surface. A photograph of a bearing specimen is shown in Fig.2. Pendulum weight was 900 lb.

The shaft and bearing specimens were fabricated to the following specifications:

Shaft diameter - $1.000^{+0.004}_{-0.000}$

Shaft surface roughness - 3 to 8 μ in. rms

Shaft length - 10 in.

Unsupported shaft length - 7 in.

Bearing internal diameter - This dimension adjusted depending on bearing-shaft material combination so that a 10-mil diametral clearance was achieved at temperature

Bearing-land width - 0.060 in.

Span between lands - $1\frac{1}{2}$ in.

¹ Underlined numbers in parentheses designate References at the end of the paper.

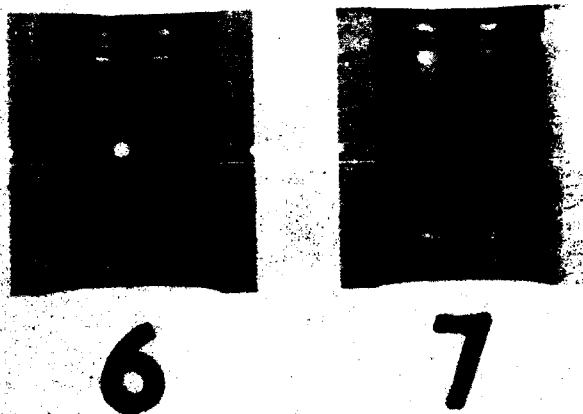


Fig. 2 Specimen pendulum bearing showing contact lands and lubricant feed hole

Bulk bearing temperature was measured by means of a thermocouple inserted through a hole in the top of the Inconel bearing housing and into a well drilled part way through the bearing wall and located halfway in from the end of the bearing.

Lubricant was supplied to the bearing through a hole in the center of the bearing which was connected with a lubricating channel in the Inconel housing. Lubricant was applied in the form of paste or slurry with a grease gun.

Operation of Pendulum

Operation of the pendulum apparatus was quite simple. The material to be evaluated as a bearing material was fabricated into a sleeve and mounted in the Inconel heat block. This was then bolted to the pendulum weight arm and a test shaft slipped through the bearing and clamped to the journal supports on the frame using split cast-iron plain pillow blocks. Transite sleeves slipped over the shaft ends were used to insulate the shaft thermally from the frame. A high-intensity infrared-lamp furnace was then fitted over the heat block. The pendulum arm was displaced 45 deg and secured by a triggering mechanism. When the desired bearing temperature was reached and stabilized, the trigger was released and the pendulum allowed to swing free. Pendulum motion was monitored through a servosystem and recorded on a recording galvanometer.

This apparatus was operated at bearing temperatures as high as 1500 F.

Determination of Friction Coefficient

The mathematical derivation of the friction-

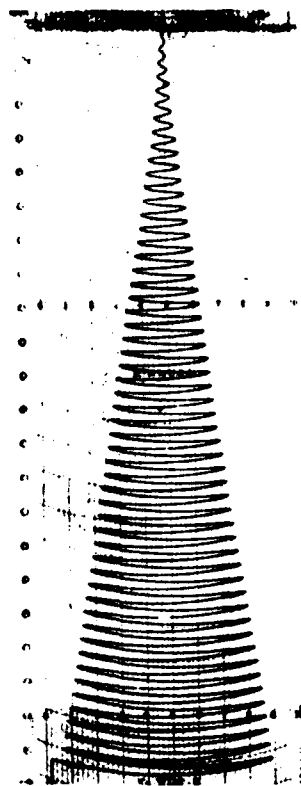


Fig. 3 Recording of damped pendulum oscillation using aluminum bronze as a pivot bearing

Calculated coefficient of friction = 0.25

Total number of swings = 108

coefficient relationship was derived for the Battelle pendulum using a simplified equation of motion developed by Kyropoulos (2). The relationship is as follows:

$$\mu = \frac{2L}{d} \frac{(A_0 - A_n)}{4n} \quad (1)$$

where

- μ = average coefficient for sequence of oscillations analyzed
- L = distance between center of test bearing and center of gravity of pendulum (37 in.)
- d = bearing internal diameter
- A_0 = amplitude at beginning of a series of oscillations, radians
- A_n = amplitude after n swings of the pendulum, radians
- n = number of swings between A_0 and A_n

A sample chart record of a free drop of the pendulum is shown in Fig. 3. Since μ , the coefficient of friction, is proportional to the inverse of n , it can be related to the total number of swings required to bring the pendulum to rest. When considering the total number of pendulum

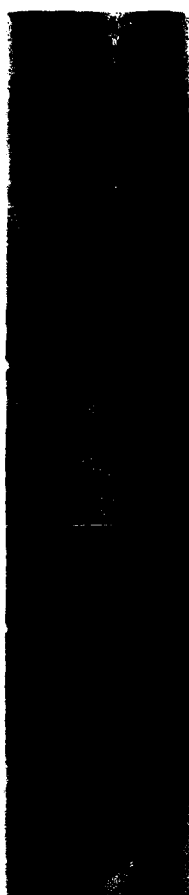


Fig. 4 Appearance of pendulum shaft after bearing evaluation at 1000 F with metal-free phthalocyanine lubricant (X2 reduced to half size for reproduction)

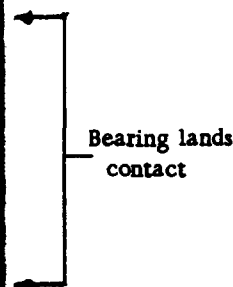


TABLE 1 TYPICAL RESULTS OF HIGH TEMPERATURE OSCILLATING BEARING EXPERIMENTS PERFORMED ON PENDULUM APPARATUS

Bearing Material	Journal Material	Lubricant	Bearing Temperature, F	Average Friction Coefficient	Performance
S Inconel	Nitrided 16-25-6	Metal-free Phthalocyanine	1000	0.1	Bearing surfaces burnished, no damage
S Inconel	Nitrided 16-25-6	None	1200	0.4	Bearing surfaces burnished, slight wear of S Inconel
Hot-Pressed SiC-Nimonic Cermet	16-25-6 Alloy	None	1000	Above 0.8	Severe abrasion damage to journal
S Inconel	Nitrided 16-25-6	Boron Nitride	1200	0.47	Abrasive wear of bearing surfaces. No indication of lubricant coating
S Inconel	Nitrided 16-25-6	Copper Phthalocyanine	800	0.30	Bearing wore and galled slightly
S Inconel	Nitrided 16-25-6	Yellow Lead Oxide	1500	0.26	Shaft burnished some blistering in burnished areas
Aluminum Bronze	16-25-6 Alloy	Silicone Grease	600	0.37	Metal transfer of bronze to shaft

Material Compositions												
	Mn	Mo	Cu	Fe	Mn	Si	Cr	C	N	Ti	Al	S
S Inconel	68	--	0.5	8.5	1.0	5.5	15.5	0.20	-	-	-	0.008
16-25-6 Alloy	25.0	6.0	--	50.0	1.35	0.70	16.0	0.10	0.15	-	-	-
Nimonic 75	76	--	--	2.4	0.4	0.6	20	0.12	-	-	0.4	0.06
Aluminum Bronze	0.02	--	99.0	0.04	0.03	1.92	--	--	-	-	7.03	-

(SiC Nimonic cermet made by hot pressing mixture of 10% SiC and 90% Nimonic 75 powders.)

levels. Performance was based on pendulum bearing friction and appearance of bearing surfaces. All lubricants investigated were applied in the form of grease or paste. Those solid lubricants which could not be obtained as true greases were mixed in a liquid carrier which volatilized at temperature.

Many of the materials evaluated behaved poorly as oscillating bearings. Often the pendulum would shudder to a halt after a relatively few swings accompanied by loud squeaking. Bearing surfaces would gall and become severely damaged or wear rapidly, filling the bearing with black debris.

A few of the materials and lubricants chosen, however, were outstanding in their performance and their relative performances are summarized in Table 1. Other material combinations and lubricants tried are included for purposes of comparison. When lubricants were used, bearing friction decreased and tendency for surface damage decreased. A few materials were found capable of withstanding dry operation at temperatures above 1000 F. One such material combination, heat-treated S-Inconel versus nitrided 16-25-6, operated at 1200 F for several hundred oscillations with an average coefficient of friction of 0.40 and with no apparent surface damage. As will be noted, when a hot-pressed Nimonic cermet was used as a bearing material severe surface damage occurred. These materials will be discussed further.

oscillations, A_n in (1) becomes 0 and the friction relationship reduces to $\mu = 2L/4dn$ or k/n , where k is made up of the pendulum constants L and d . By plotting μ as a function of total number of swings, the friction coefficient can be estimated from such a chart and by counting the number of swings of the pendulum until it comes to a full stop. This method proved satisfactory for routine evaluations. It was proven by graphical analysis of data from 100 free falls of the pendulum apparatus, which produced a close grouping of points about a hyperbolic curve. This value will be an average value and depends upon the constancy of the pendulum friction. Generally it was found that in most free falls where galling or excessive wear did not occur, friction remained relatively constant as the oscillation decayed.

Pendulum Experiments

A number of bearing materials and solid lubricants were investigated at various temperature

Analysis of Successful Pendulum Bearings

Superalloys were selected for investigation

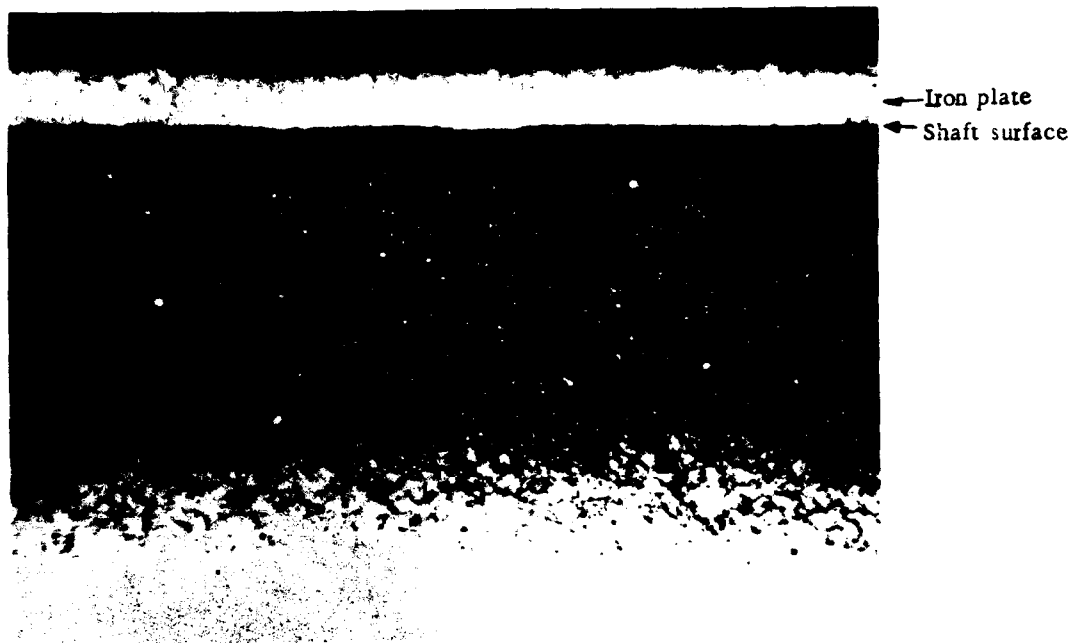


Fig. 5 Photomicrograph of sectioned 16-25-6 shaft nitrided after operation in an airframe bearing machine for a total of 20 hr (intermittent) at 1000 F (X500)

as journal materials for 1000 F and higher because of their oxidation resistance and toughness. It was found relatively early in the investigation that hot hardness was a requisite for successful high-temperature bearing operation. Superalloys did not possess the hardness level required. Surface-hardening by nitriding was found feasible with the iron-base 16-25-6 alloy. Nitriding was accomplished by heating the finished shaft to 1200 F in flowing NH_3 , dissociated 35 per cent, for 72 hr. The resulting case depth was 4 mils and its average hardness 643 KHN ($\sim 50 R_c$). Average core hardness was 221 KHN.

When this shaft was operated at 1000 F and above with an age-hardened S-Inconel bearing, operation was smooth with little or no surface damage. An example of a typical post-test shaft surface is shown in Fig. 4. The burnished tracks are the bearing contact zones (shown by the arrows) and are typical of surfaces characterizing successful operation.

Examination of the wear tracks by light microscopy revealed a burnished continuous film where surface rubbing had occurred. Some pitting and blistering of this film was noted on specimens operated in the neighborhood of 1500 F.

The film structure and substrate were investigated in metallographic sections. Surface conditions were preserved by plating before sectioning. Samples of nitrided shaft specimens, operated at 1000 F for 20 hr with S-Inconel bearings, were studied extensively. Fig. 5 shows a typical section including the nitrided case. When this

section is compared with a pretest specimen shown in Fig. 6, it will be noted that the outer "white" layer had disappeared and some inward diffusion of the nitrided case along grain boundaries can be seen. Hardness traverses of the case indicated slightly lower average case hardness and a deepening of the case.

Difficulty was experienced in making metallographic sections because of the reluctance of a number of metals to form an adherent electrodeposited layer over the burnished zones. During mounting and polishing, the plated layer tended to pull away from the outer surface. However, iron plating was found sufficient to prevent crumbling away of surface layers during sectioning. After examination of a number of specimens, sections were found containing some areas where the outer layers were intact. From these analyses it became evident that the wear surface was a two-phase oxide layer. A section of the oxide layer is shown in Fig. 7. This is a section through the black shiny wear track which was observed in connection with successful high-temperature operation. The inner oxide phase appears to be penetrating the metal substrate along grain boundaries. The outer phase, averaging 0.00025 in. thickness, appeared more continuous. Carbides from the original alloy could be seen imbedded in the outer oxide matrix. These could not be resolved in the photomicrograph.

Sections of the shaft were also made in the areas where no rubbing contact had occurred. The same two-phase oxide layer was in evidence but

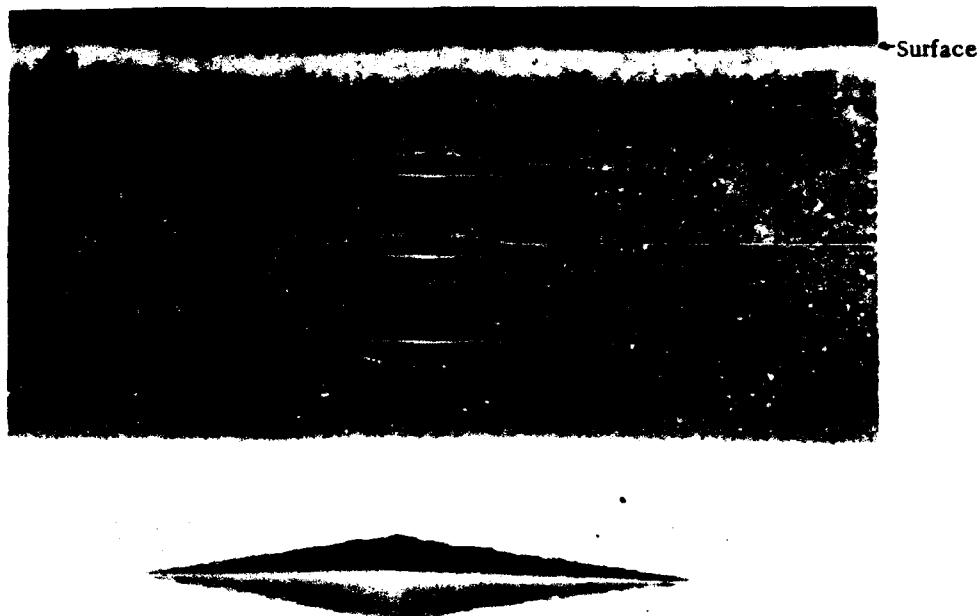


Fig. 6 Photomicrograph of edge of 16-25-6 alloy cylinder showing the nitrided case depth and structure (X500). Diamond-shaped marks are Knoop hardness indentations. Cracks near surface occurred during sectioning for metallographic examination

appeared much thinner in section. The outer phase of the oxide layer on the "burnished" specimen in particular was thicker.

Attempts were made to analyze the surface layers in the shaft wear tracks. X-ray diffraction analysis of the shaft surface with a diffractometer revealed a spinel structure. Attempts to analyze the surface of the spinel by electron-diffraction techniques produced only a diffuse pattern. It is suspected that the shiny material on the surface is a thin film of amorphous glassy material -- perhaps SiO_2 the silicon being supplied by the S-Inconel bearing material.

SIGNIFICANCE OF ANALYSES

The results of the experiments using 16-25-6 alloy shafts seem to indicate that successful high-temperature bearing operation can be achieved by the production of a tough tenacious oxide film on the appropriate alloy surface. Spinel is often found on chromium-nickel-iron stainless steels (4, 5) and are generally recognized as "tighter" structures than single metal oxides. As a result, oxidation rate of materials which form spinels is generally slower than materials with one oxide, and the resulting scale is less apt to contain voids, cracks, fissures, or other discontinuities. Such a surface will provide a surface of low surface energy and therefore reduce adhesion tendencies. It is possible in the

bearings evaluated that high-temperature lubrication was provided by a film of SiO_2 formed by reaction of silicon in the S-Inconel with oxygen at the sliding interface. The amorphous film which produced a diffuse electron-diffraction pattern may be a glassy SiO_2 or complex silicate.

Of interest was the observed tendency for the oxide layers to be thicker in the zones where rubbing contact had occurred. Owing to the presence of carbides in the spinel layer, it can be surmised that oxidation occurred by diffusion of oxygen to the metal-oxide interface. Diffusion processes are influenced by lattice defects in the oxide layer. Presumably heavy stressing of the oxide layers by the bearing action could generate more defects and increase the rate of oxygen-ion diffusion. Opening of fissures into the oxide layer would also markedly increase the oxidation rate.

The results of the analyses of these few high-temperature bearing materials lead to some interesting speculations. There are multitudes of oxide structures which have been found in high-temperature scales. Perhaps there are oxides which could be formed on specially concocted alloys which would provide as good or better performance under sliding conditions as the 16-25-6 alloy. Oxide structures can be altered by the incorporation of small amounts of impurities which change the concentration of ion defects. It is reported that dark-green NiO can be transformed



Fig. 7 Photomicrograph of section of nitrided 16-25-6 shaft after bearing operation for 20 hr taken in "burnished" area subject to rubbing by S-Inconel bearing (X500). Note oxide layers on surface

into a yellow-green oxide by adding 0.1 to 1 mole per cent of In_2O_3 (6). Additions of small amounts of such materials to metal alloys might be used to slow down "abrasion-activated" oxidation or to alter the resulting complex oxide to produce more desirable properties. There is little doubt that the oxide layers which are formed on surfaces subject to rubbing or abrasion are different from those which form in the open air. Study of these "abrasion oxides" would be of immense value in the understanding of high-temperature bearing phenomena and should be powerful means for developing better high-temperature bearing materials.

ACKNOWLEDGMENTS

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